Amorphous Metal Ribbons and Metal Amorphous Nanocomposite Materials Enabled High-Power Density Vehicle Motor Applications

Product ID: ELT256

Principal Investigator & Presenter: Michael E. McHenry
Carnegie Mellon University

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Overview

PI: Michael E. McHenry, Carnegie Mellon University (CMU), Pittsburgh, PA

Key Collaborators & Roles: Maarten DeBoer, CMU (Mech. Prop.); Kevin Byerly, CMU (Advanced Manufacturing); Satoru Simizu, CMU (Motor Design & Losses); Subhashish Bhattacharya, NCSU (Controls); Eric Theisen, Metglas (Casting Tech.)

Total Project Cost: $0.7 M

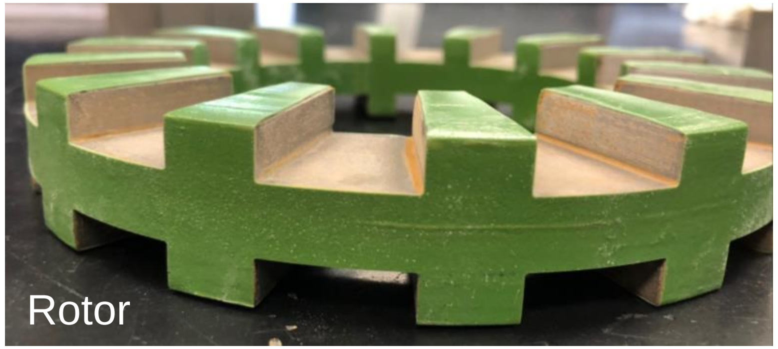
Project to Date Cost: $0.27 M

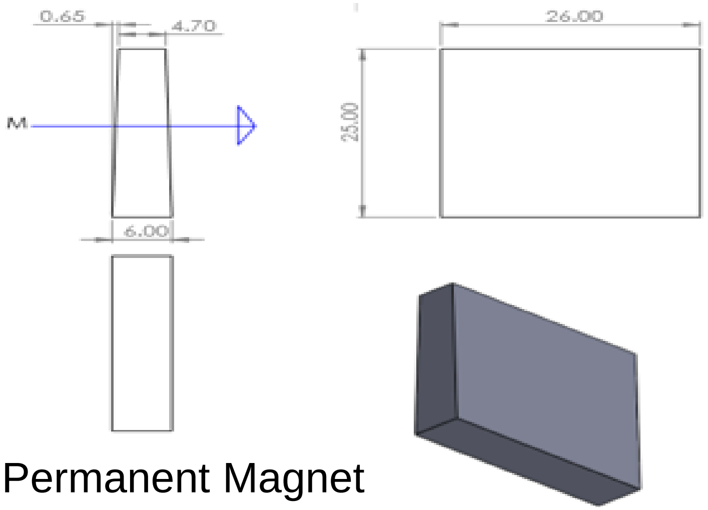
Project Duration: Year 1.5 of Three Years

- ***Relevance***:
  - Materials and manufacturing technologies to achieve ***8-fold increase*** in power density for a traction motor design to showcase Amorphous Metal Ribbon (AMR) and Metal Amorphous Nanocomposite (MANC) materials.
  - 8-fold increase in power density for traction motors are enabling for electric vehicles (EVs).
  - Designs address criticality of rare earth elements (REEs) in hybrid designs ***without*** heavy REEs.
- ***Approach***:
  - ***BP 1 – Benchmark AMRs and MANC Alloys for Traction HSM Design***: AMRs will be benchmarked, in a Finite Element Analysis (FEA) model. Alloys will be cast at commercial scale and properties relevant to 5 kHz magnetic core losses and audible magnetostrictive loss will be measured and compiled. Sample ribbons will be provided to the DOE. A FEA model of a Traction High Speed Motor (HSM) has been designed and performance numerically evaluated.
  - ***BP2 – Properties Optimization, Component Fabrication and Alloy Studies***: Properties of AMRs will be optimized and benchmarked. Rotors and stators will be evaluated. Magnetic switching frequencies and mechanical properties will be evaluated. Measured properties are incorporated into a FEA model of a Traction HSM to be used to finalize the design.

Project Objectives and Deliverables

- ***Objectives*:**
  - Traction motor design showcasing AMR and MANC materials.
  - Low-loss, 2” wide, AMR and MANC materials evaluated at 5 kHz.
  - FEA assessment of technology design to verify 8x increase in power density.
  - Demonstrate manufacturability of AMR/MANC HSM motor.
- ***Deliverables*:**
  - Motor Components: (a) Machined heavy-RE free permanent magnets stator sections; (b) AMR and/or MANC rotor sections; (c) engineered Cu windings for stators; (d) methods for materials post processing to yield low losses at the high switching frequencies. ***Complete***
  - FEA assessment of preliminary technology design has been completed, verifying an 8x increase in power density to be achievable. (06/15/21)
  - Evaluate mechanical properties limitations at high motor speeds. (03/15/22)
  - Evaluate oxidation/lamination to limit eddy currents. (06/15/22)
  - Report power densities for AMRs and MANCs. (09/15/22)



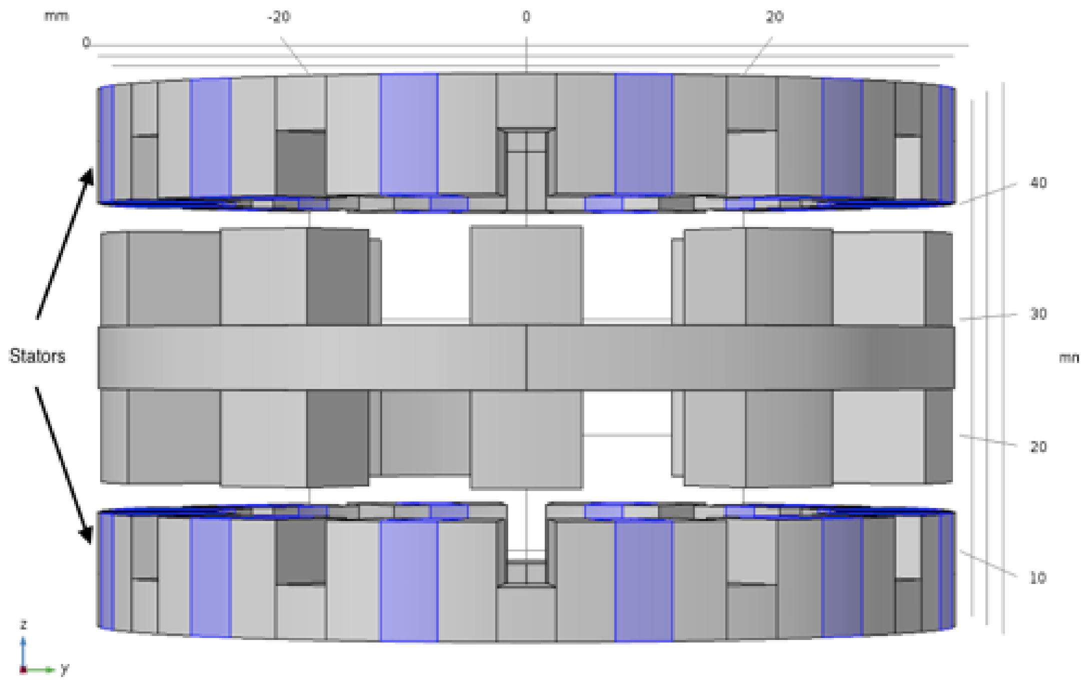


Permanent Magnet

Approach

- ***Benchmark 2.5 kW Flux Switching with Permanent Magnet (FSWPM) Axial Motor Design*:**
  - 3-phase motor with dual stator & 14 rotor poles
  - 6000 rpm; 1.4 kHz switching; RE-free ferrite magnets
  - 80 mm outer & 50 mm inner radius
  - 5.4 kg & 1.5 L envelope. 2.5 kW & 4.0 Nm torque

	Fe-Ni MANC	3% Si-Steel
Fe loss: 2.5 kW	3.4 W	133 W
Cu loss (7.5 A)	27 W	27 W
Total	30 W	160 W
T-rise	27 ˚C	145 ˚C

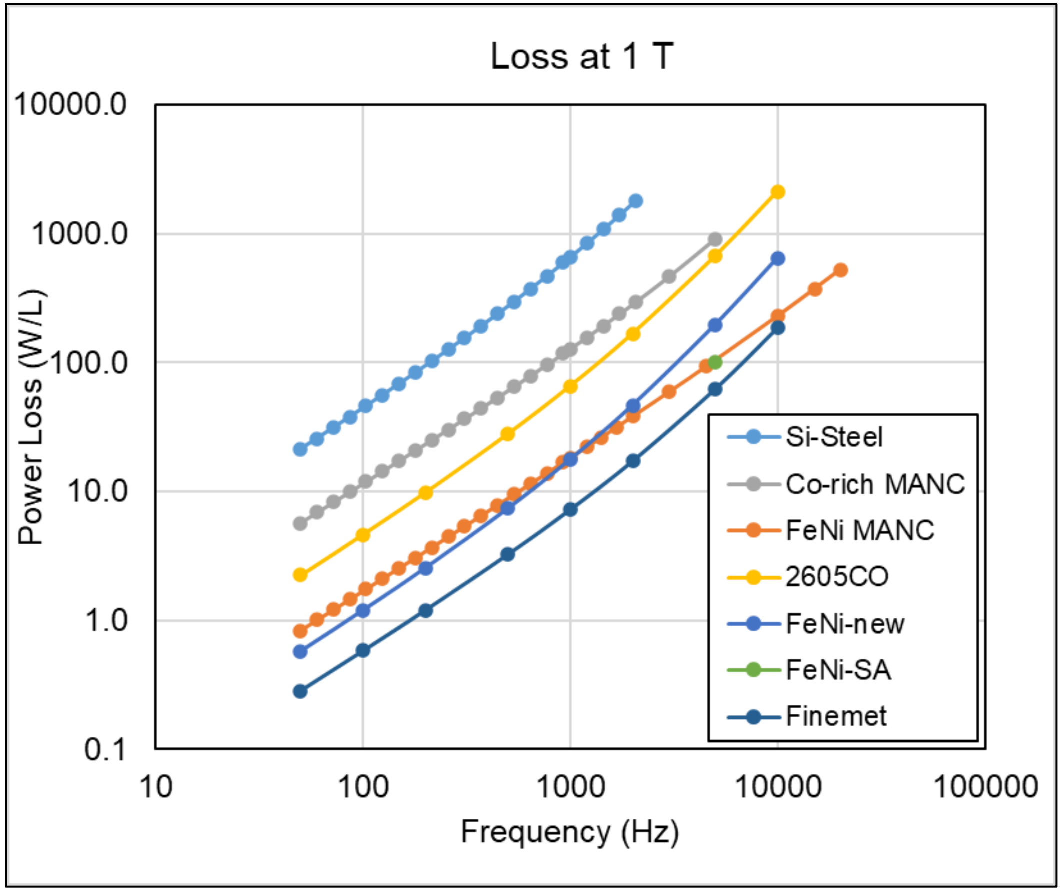


Grey: Fe-Ni based MANC **Blue: Ferrite PM**

FSWPM Axial Motor Utilizes Patented CMU Fe-Ni based MANC Materials

Approach

- ***Amorphous Metal Ribbon (AMR) and Metal Amorphous Nanocomposite (MANC) Materials as Benchmarked with Silicon Steel***:



Soft Magnetic Material	Frequency Limit (10 W/kg loss)	1 T Design	1.7 T Design	Comments
3% Si-Steel	150 Hz	1.0 kW	2.7 kW	
2605CO	1 kHz	6.7 kW	18 kW	
FeNi-80	3 kHz	20 kW		
FINEMET	5 kHz	33 kW		Mechanically fragile

Several AMR/MANC Materials were Examined to Determine Frequency Dependency of Power Loss

Technical Accomplishments and Progress

- ***Subtask 1.1.1*: Allocated Staff for the Project**
- ***Subtask 1.1.2*: Obtained FEA Software for Electromagnetic, Thermal, and Mechanical Modeling**
- ***Subtask 1.1.3*: Identified Suppliers of Rare-Earth Permanent Magnets (NdFeB)**
- ***Subtask 1.2.1*: Benchmarked Conductors / Rare-Earth Permanent Magnets in FSWPM HSM Design**

Conductor	Resistivity (Ωm)	Power Loss @ 6 A/m^2	Density (kg/L)	Coil mass (kg)
Aluminum	2.5 x 10-8	52	2.70	0.16
Copper	1.6 x 10-8	34	8.96	0.52

- ***Subtask 1.2.4*: Quote and Purchase from Permanent Magnet Source (Quadrant Magnetics)**

Magnet type	Remanence (T)	Intrinsic Coercivity (kOe)	Magnet Size [tapered] (mm)	Comments
Ceramic 8	0.39	3.2	25 x 30 x [6.5 ~10.5]	
N38 (NdFeB)	1.20	12.0	25 x 26 x [4.7 ~ 6.0]	Dy: 0~1.5%

Technical Accomplishments and Progress

- ***Subtask 1.2.2:*** Benchmark New Materials in Prior FSWPM HSM Design
  - Enhancing specific power of the prior 2.5 kW to 20 kW involves a variety of changes…

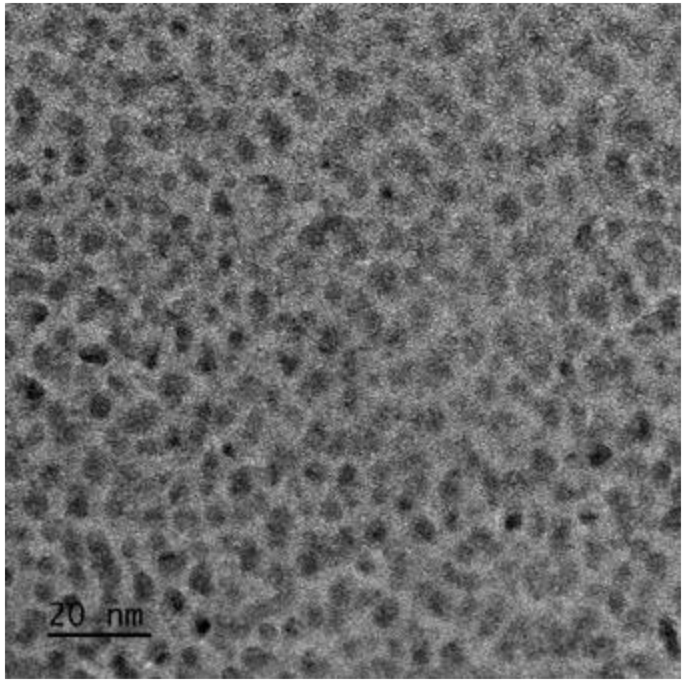
Parameters	Initial (2.5 kw)	High Power (20 kW)
Electrical Speed	1400 Hz (14 poles)	2100 Hz (21 poles)
Inner/Outer Radius	50 mm / 80 mm	90 mm / 115 mm
Flux Density (peak)	0.60 T	1.53 T
Permanent Magnet	Ferrite (B_r = 0.4 T)	NdFeB (B_r = 1.2 T)
Current Density (peak)	6.0 A/mm2	18.0 A/mm2
Conductor Fill Factor	54%	60%
Torque	4.2 Nm	59 Nm
Power (at 6000 rpm)	2.6 kW	37 kW
Copper Loss (DC)	34 W (1.3 %)	230 W (1.3 %)
Iron Loss (at 6000 rpm)	7 W (0.3%)	82 W (0.2%)
Motor Mass	5.8 kg	9.9 kg
Specific Power	0.45 kW/kg	3.8 kW/kg

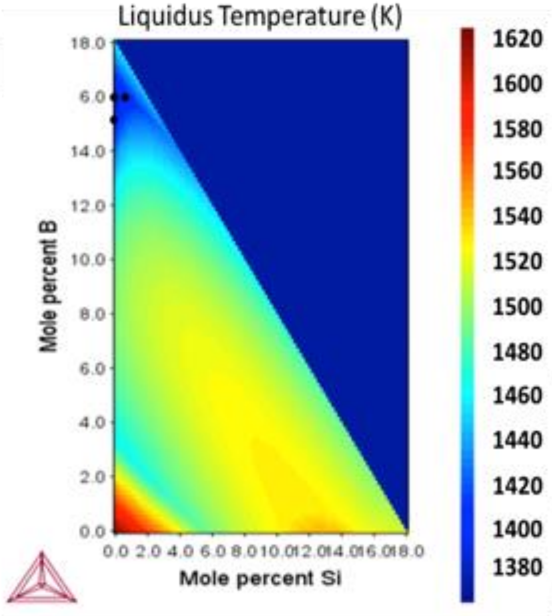
Technical Accomplishments and Progress

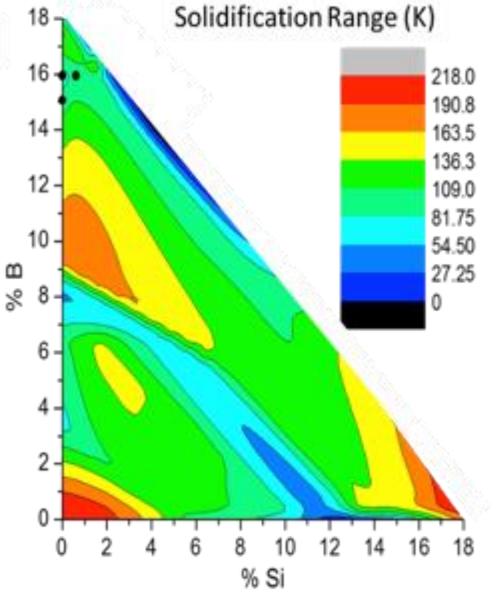
- ***Subtask 1.2.3***: Begin Casting New Fe-Ni based MANC Alloys

Established glass forming ability in alloys with increased Fe-Ni

Direct casting into nanocomposite for certain alloys







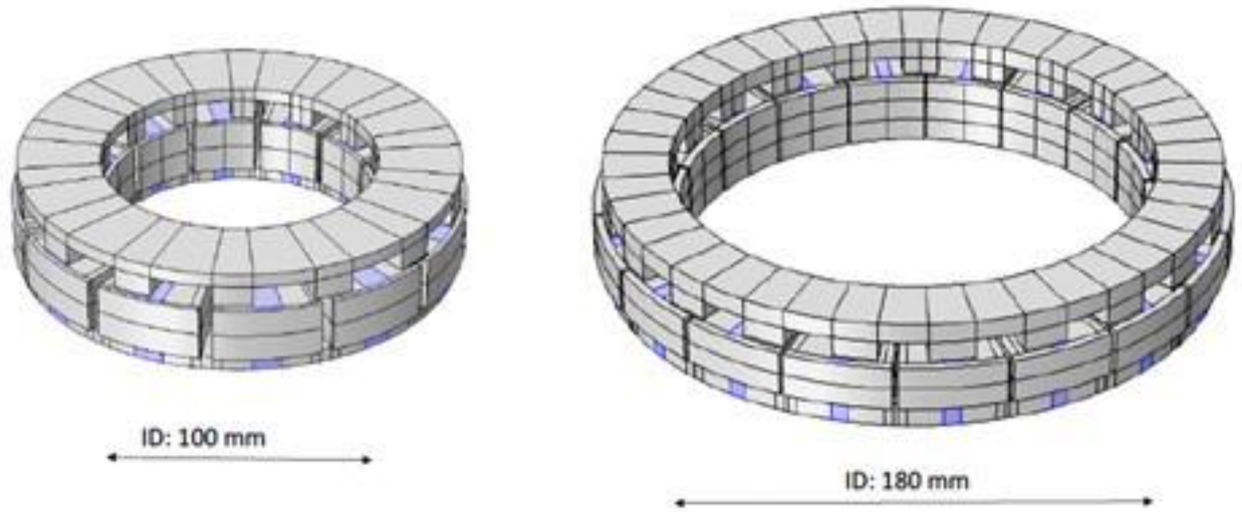
	$(Fe_{70}Ni_{30})_{82}B_{15}Si_0Nb_3$	$(Fe_{70}Ni_{30})_{82}B_{16}Si_0Nb_2$	$(Fe_{70}Ni_{30})_{82}B_{16}Si_1Nb_1$	$(Fe_{70}Ni_{30})_{85}B_{14.5}Nb_{0.5}Si_0$
$T_{c(amorphous)}$ (°C)	407	417	438	462
B (Tesla)	1.32	1.36	1.28	1.48
H_c (A/m)	37.6	30.0	30.7	26.0

Milestone Tracker

Milestone	Description	Planned Completion Date	Actual Completion Date
Budget Period 1			
Design Traction Motor	Benchmark materials. Report FSWPM motor power losses.	6.15.20	6.22.20
AMR Loss at 5 kHz Evaluation	Compare wide cast AMR and MANC ribbons at 5 kHz	12.15.20	12.15.20
Evaluate Materials in Traction Motor Design	Complete power density improvement evaluation with AMRs and MANCs	4.15.21	4.14.21
Preliminary Design Validated to Achieve Performance Measures	FEA assessment of preliminary technology design to verify 8X increase in power density.	6.15.21	-
Budget Period 2			
Fabricate Stator and Rotor Parts	Demonstrate manufacturability of proposed 20 kW axial motor	12.15.21	-
Evaluate Mechanical Properties of AMRs and MANCs Suitable for HSM	Use mechanical properties in FEA to verify that HSM is mechanically able to rotate at >20krpm	3.15.22	-
Report Oxide Properties for AMR and MANCs	Demonstrate resistance > coated laminates. Demonstrate bulk resistivity > 150 µΩ-cm, surface resistivity > 500 µΩ-cm	6.15.22	-
Test AMR and MANC Dual Stators and Rotors	Report HSM power density for each material	9.15.22	-

Proposed Future Work (BP2)

- ***Conductor Fabrication*:** Rapid prototyping will be used to investigate several magnet wire types/sizes.
- ***Demonstrate Rotor / Stator Manufacturability*:** Core fabrication and post-processing will be explored to demonstrate rotor and stator parts.
- ***Demonstrate Ribbon Layer Electrical Isolation*:** Report oxide properties for AMR and MANCs.
- ***Evaluate Mechanical Stability at 20 krpm*:** Use mechanical properties in FEA to verify that HSM is mechanically able to rotate at > 20krpm.



Initial Traction Motor Design Complete, Enabled by Patented CMU Fe-Ni based MANCs

Collaboration and Coordination with Other Institutions

Principal Investigator: Michael McHenry, 412-268-2703, mm7g@andrew.cmu.edu
CMU Co-Investigator: Prof. Maarten DeBoer
CMU Senior Scientist: Satoru Simizu
Graduate Students: Yuval Krimer, James Egbu, Kyle Schneider , Walter Robinson

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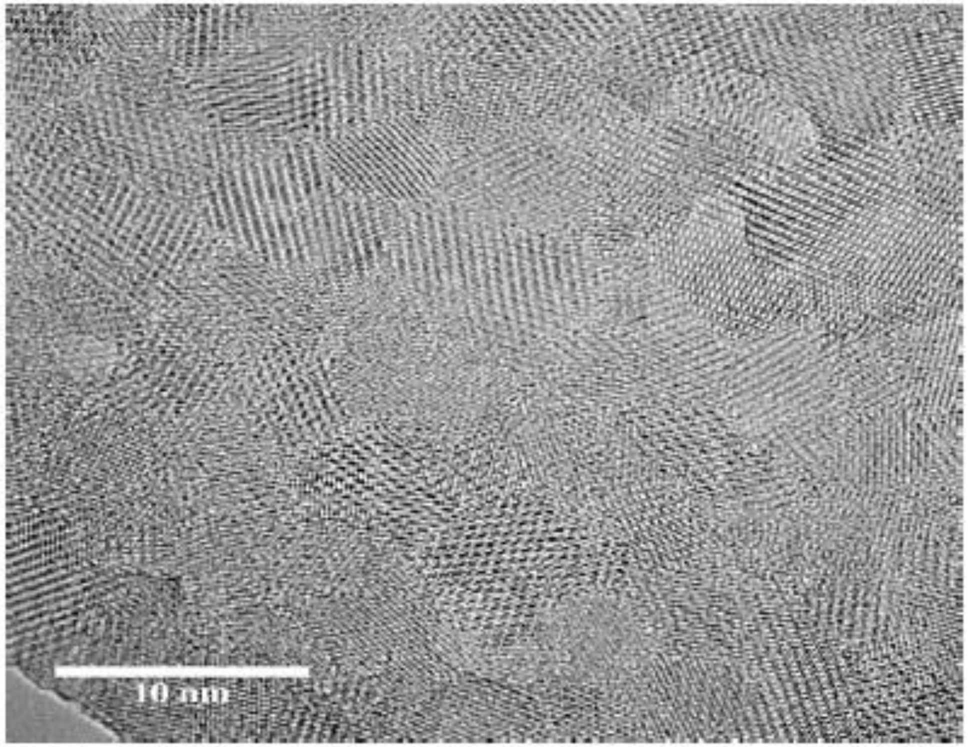
Summary

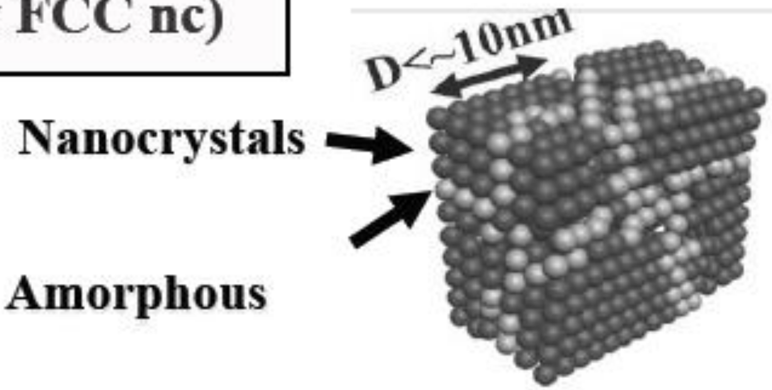
- ***Project seeks to demonstrate high speed motor efficiencies opening new markets for AMR and MANCs in traction motors.***
- ***New MANC commercial production capabilities identified*****:**
  - Metglas has a license to test Fe-Ni based MANCs and has new FeCo-based AMRs.
- ***Commercialization approach*****:**
  - Technology transfer New Alloys to Metglas
  - Design new traction motor topologies.
  - Demonstrate potential scaling to 20 kW motors.
  - Identify permanent magnets and topologies with no use of heavy rare earth elements (REEs).
  - Identify manufacturing methods of AMR's and MANCs for axial motor topologies.
- ***Industrial Consortium and Start-up*****:**
  - Univ. of Pittsburgh, Carnegie Mellon Univ. and NCSU formed a Consortium: **Advanced Magnetics for Power and Energy Development (AMPED)**. The AMPED consortium will serve as an advisory body to assess future markets and industrial needs. **Metglas** & **Eaton** joined as AMPED partners .
  - CMU has licensed MANC IP to **CorePower Magnetics** https://www.corepowermagnetics.com. CorePower Magnetics is bringing high performance power electronics components to market, building on soft magnetics technologies invented at CMU.
  - Licensing of CMU soft magnetics technologies through CorePower provides an avenue for further commercialization.

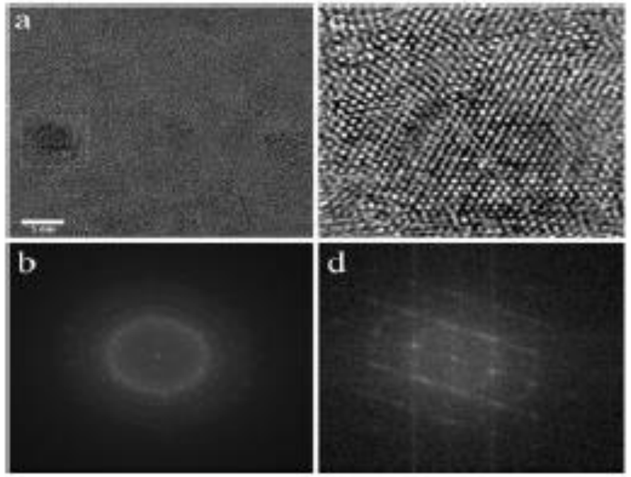
Technical Back-Up Slides

Technical Back-Up Slides

Metal Amorphous Nanocomposites (MANCs w FCC nc)







Ferromagnetic Nanocrystals Embedded in Amorphous Matrix (MANC):
Nanocrystals → High Induction
Matrix → Small Grain Size and Large Resistivity   Composite → Low Losses

Technical Back-Up Slides

Experimental: $(Fe_{70}Ni_{30})_{80}Nb_4Si_2B_{14}$

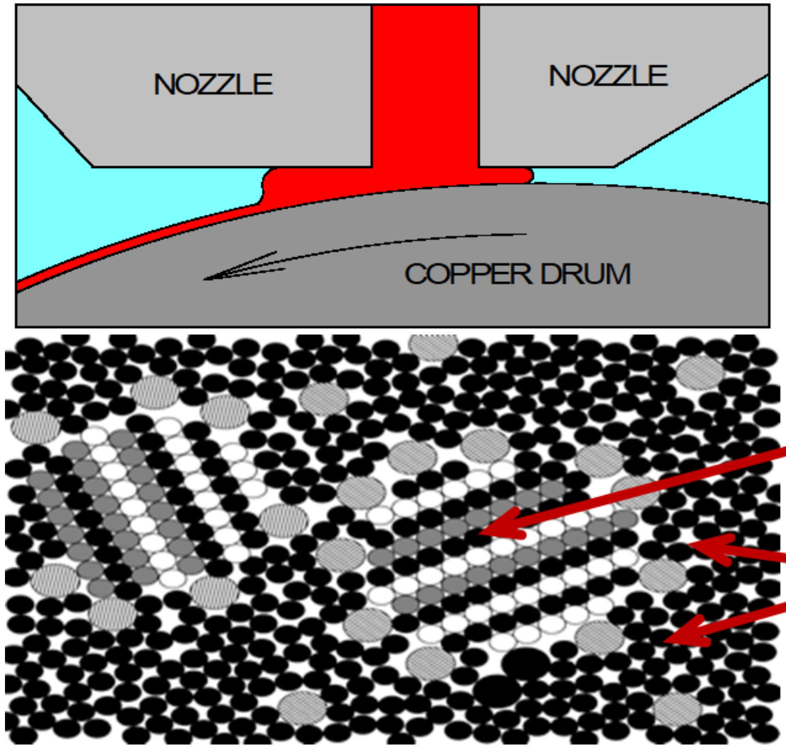
(MANC) alloys produced by PFC: TE = V, Cr, Mo, Nb

$(Fe_{70}Ni_{30})_{80-x}Nb_4Si_2B_{14}TE_x$ $(0 \le x \le 5)$ substitute for (FeNi)

$(Fe_{70}Ni_{30})_{80-y}Nb_{4+y}Si_2B_{14}$ $(0.5 \le y \le 2)$) substitute Nb for (FeNi)

Annealed at 440 °C and strain-annealed at 440 °C and 300 MPa

TE = Early Transition Metal VBS Element



Resistivity from Am, NC phases and interfacial traps.

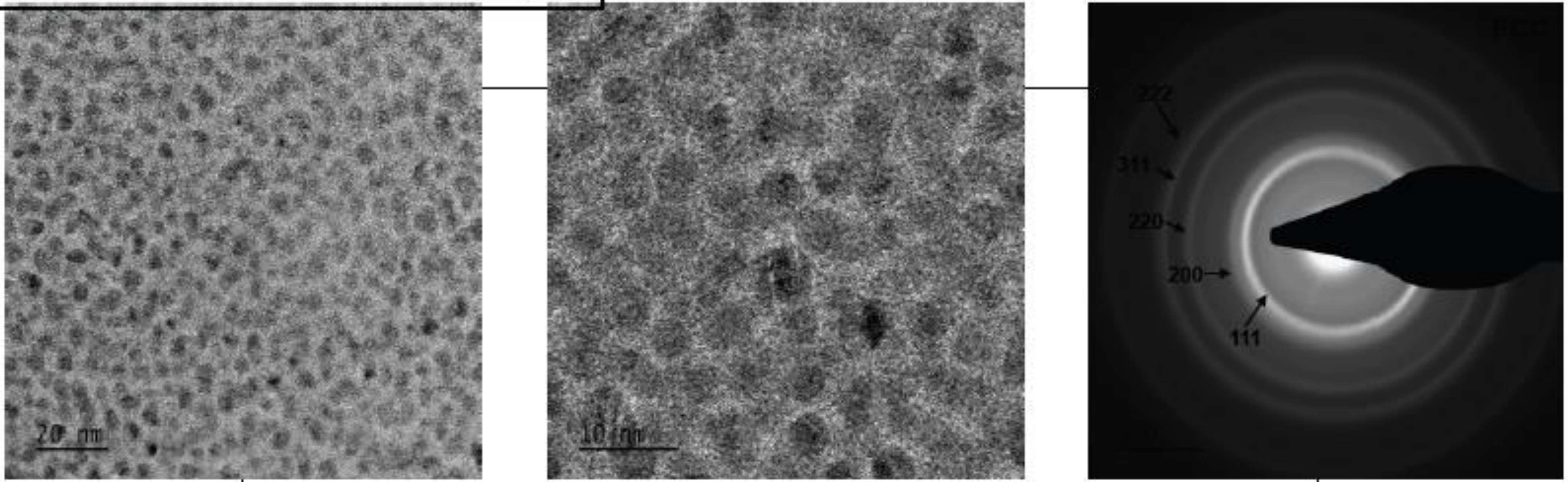
V, Cr are quite soluble in NCANDAMR

Mo, Nb are growth inhibitors interfacially trapped.

[6],[7], [14],[15]

Technical Back-Up Slides

TEM of As-Cast 85% Alloy

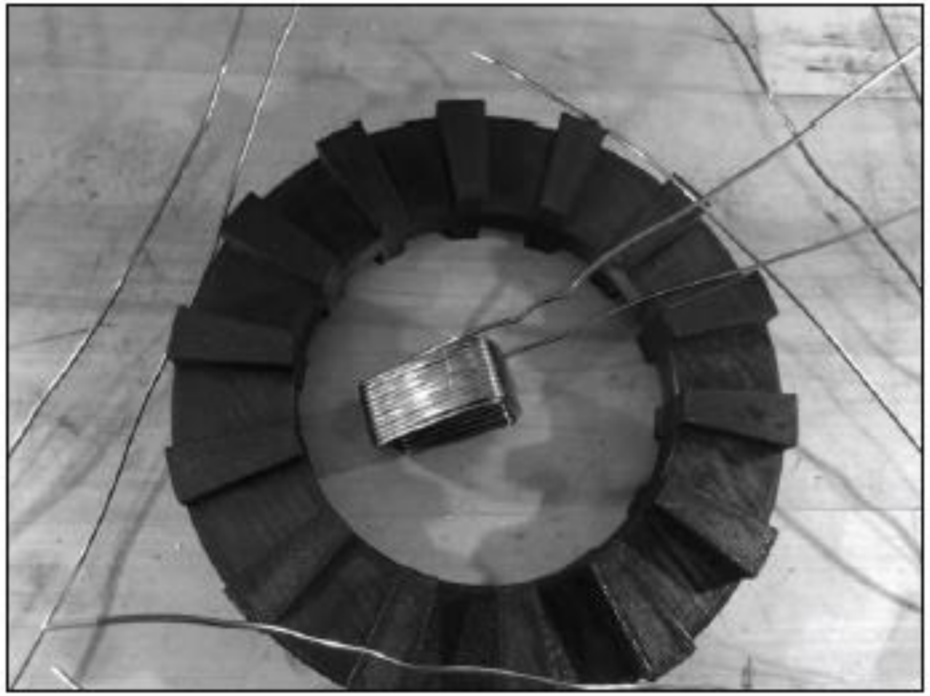


Mainly FCC Nanocrystals!

Wednesday
10:05 AM
Del Mar

Stators with coils and rotor

(3-d printed mock-up, > 50% wire fill factor)



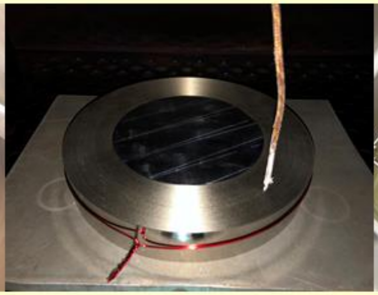
rotor

Technical Back-Up Slides

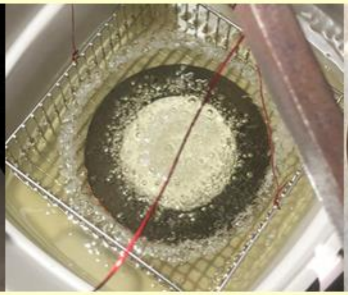
1. Tape Wound Core (3 req.):

- FeNi alloy
- 160mm X 100mm X 25mm
- ~2 kgs each

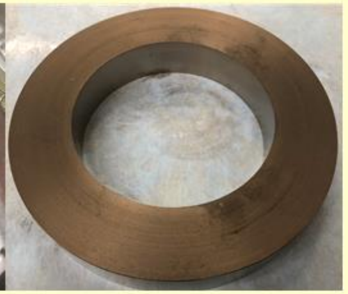
Winding



Annealing



Impregnation

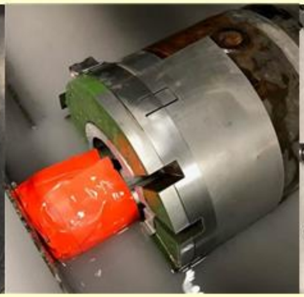


Finished Core

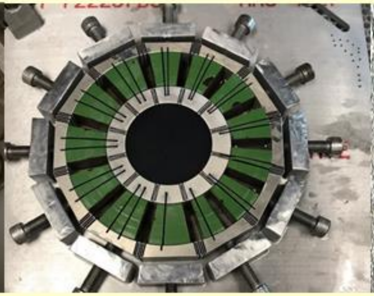
2. Water Jet Cutting:

- 2 stators (12 wedges cut from 1 core)
- 1 rotor

Custom Fixturing



Slot Cutting

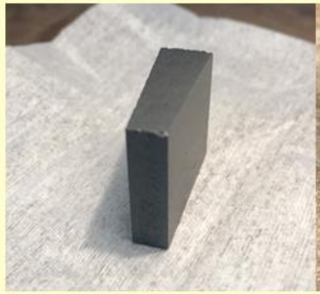


Wedge Cutting

No Layer Smearing

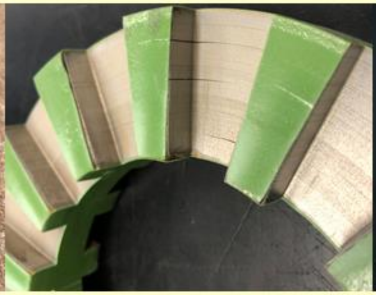
3. Stator / Rotor Parts:

- Stator (FeNi SM + ferrite PM)
- Rotor (FeNi SM)
- Copper windings



Ferrite Wedges

Stator Wedges



Rotor

Bobbin-less Coils

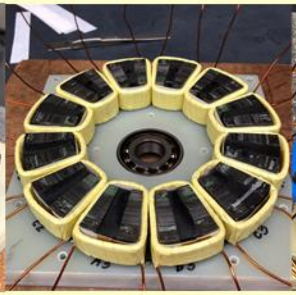
Technical Back-Up Slides

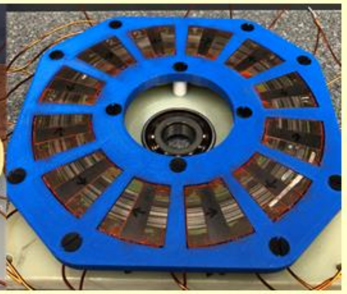
4. Stator Assembly:

- Parts epoxied together and into the FR4 backing plate
- Retainer ring for added security


Joining PM + SM


Backing Plate

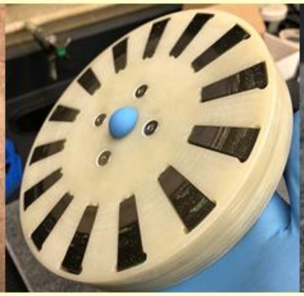

Coil Fitting

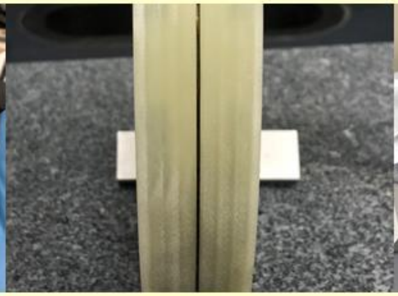

Retainer Ring

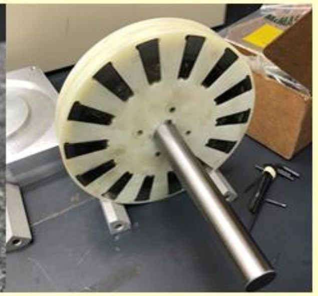
5. Rotor Assembly:

- 2-piece FR4 hub with integrated spokes + rim
- 20mm shaft


Coating Removal

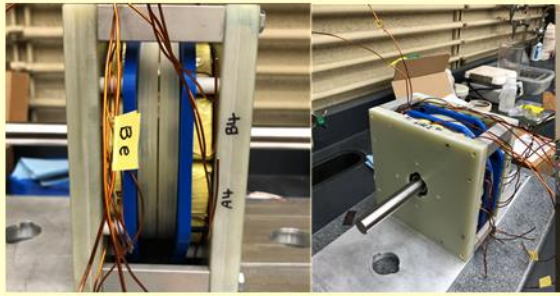

Hub Enclosure

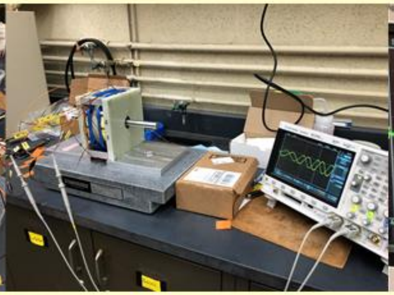

Hub Rim Close-up


Shaft Fitting

6. Motor Assembly:

- Bushings used to hold gap between rotor / stator
- Back EMF matching used to tune gap


Completed Motor Housing


Low Speed Test Setup


Back EMF Matching